Resilient “Plug-n-Play” Storage Integrated Electricity Solutions for Off-Grid Communities

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2021 DOE OE Energy Storage Peer Review
10/28/2021

GT Center for Distributed Energy

Creating holistic solutions in electrical energy that can be rapidly adopted and scaled

WORLD ECONOMIC FORUM
TOP 3 TRANSMISSION GRID INNOVATIONS
2010-2020
"Accelerating the Energy Transition"

Platform Initiatives

Grid Asset Augmentation

7.2 kV 50 kVA Hybrid Transformer

13 kV 1 MVA Modular Transformer

Smart Wires

13 kV/50 kVA FUT
13 kV 1 MW Power Router
67 MVA Modular LPT
Improving Grid Resiliency
Smart Wires
Meshed Grid VVC

Energy Access in Emerging Markets

'Exponential' Tech
Self Organizing Nano Grid
Pay-Go Smart Meter
Low Cost DA for Grids
Ad-Hoc Bottom-Up Grids
Empower a Billion Lives

Emerging Technology: D-Light

Top 10 Emerging Markets
Source: Global Intelligence Alliance

Next Generation Grid Power Electronics

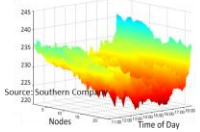
4 kV MVSI for Large PV Farms

7.2 kV 50 kVA SST

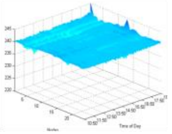
5 kV DC Grid Building Block
7.2 kV 50 kVA Grid Connected SST
4 kV MVSI for Large PV Farms
Triports for PV/Storage/Grid
MVSI with Integrated Storage
Microgrid-Grid Interface Device

Decentralized Grid Control Techniques & Markets

Grid Edge Volt VAR Control
Collaborative Control
High PV Integration
DER Micro grid Impact
Self-Pricing Island Grids
Virtual Power Plants

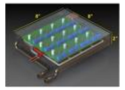


Feeder Voltage w/o and with GE Control



Feeder Voltage w/ Grid Edge Control

Next Generation Industrial Power Electronics



100 kVA EV Drive System

200 kVA Isolated Drives

2 MVA Industrial SIVOM

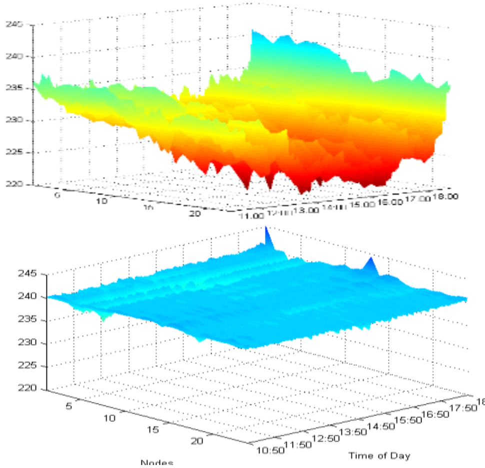
Industrial CVR Energy Efficiency
100 kVA EV Drive System
25-500 kVA Isolated Drives
Energy Hub – DC Fast Charging
Programmable Load/Source
Data Center Power Sources

Global Asset Monitoring Management & Analytics (GAMMA)

Low-Cost Communications
Cyber-Security
Data Management
AMI Data Analytics
Global Sensor Networks
Cloud Based GAMMA System

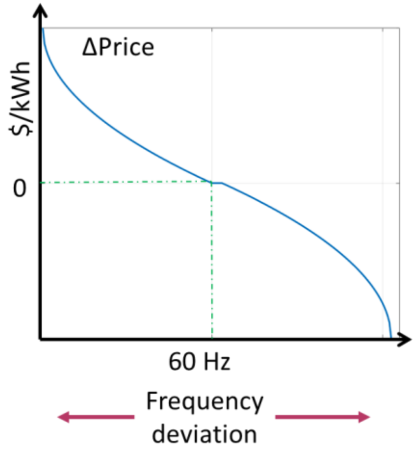
GAMMA Platform

Gamma kernel

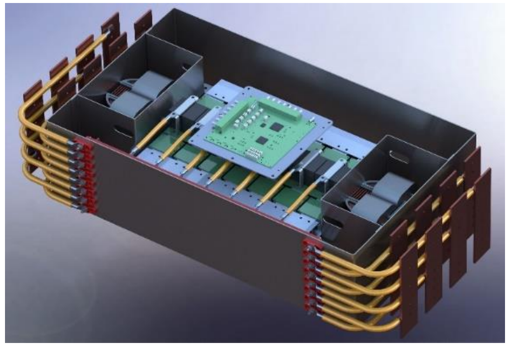


COLLABORATIVE CONTROL
Varentec

TRANSMISSION POWER FLOW CONTROL
Smart Wires



SELF-PRICING MICROGRIDS
Transactive/Physical Grid



SOLID STATE TRANSFORMER (S4T)

Exponential Technologies (outside utility influence)

Computation, PV solar, wind, EV, power semis, storage, microcontrollers, prosumers, sensors, IoT, comms, online services, social media, mobile pay, block-chain, cloud, autonomous control, AI, ML, deep learning

Primary Drivers

Digitalization

Decentralization

Decarbonization

Need for Energy Equity and Resiliency

- While most of us take the power grid for granted, there are communities that are off-grid, or live with poor-quality unreliable power
- This includes thousands of people, many living in Native American nations, or in remote areas where it is difficult to provide and maintain service
- High-impact low-frequency events (e.g., climate change, hurricanes, flooding, wildfires, cascading outages or cyber-physical events) can cause extended outages on the grid, with disproportionate impact on poorer communities.
- There is a need for a cost-effective flexible equitable solution for providing power to these communities, such that their quality of life is maintained

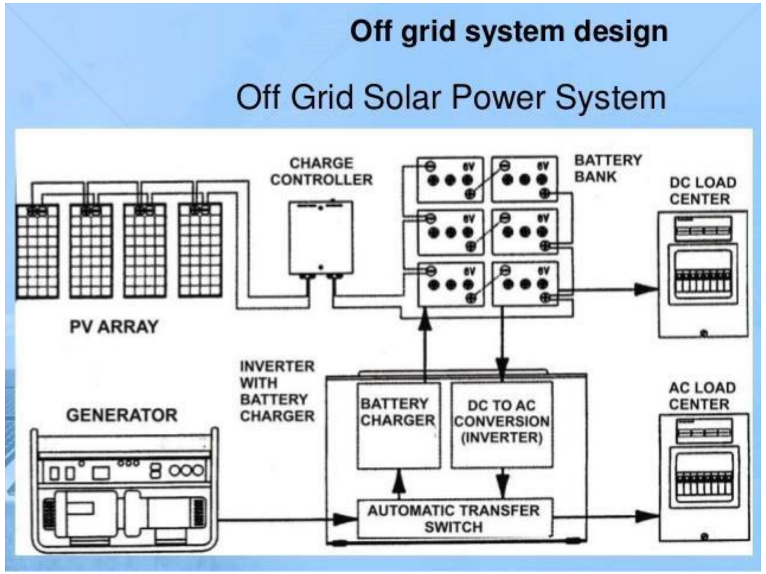
Navajo home being fitted with PV power

HILF events and grid impact

Example Off-Grid Electricity Solution

What are the Available Options?

- Resilience solutions typically include diesel generators and microgrids, which are expensive and require skilled technicians to install and operate the systems – challenging for small communities or single homes
- The other alternative is a solar home system, using PV panels & batteries – typical off-grid home may need 1 kW to >10 kW at 120 volts 60 Hz
- Typical off-grid homeowner would like to:
  - Sustain critical loads, such as lighting, phones, refrigerators and TV/internet connectivity for sustained periods of time
  - Power high-rated loads such as microwaves & appliances as needed
  - Power tools and machines that can provide livelihood
  - Start small and low-cost, expand as needed
  - High flexibility to fulfill daily requirements
  - Avoid high costs related to installation, operation, repair and disposal
- Existing state of the art solutions use PV panels, batteries, and power converters to supply single homes and are large, bulky and very expensive, poses safety hazard, is limited in expansion capability, often home rewiring – requires skilled technician to install



Typical solar home system installation

DOE Sandia Project Objectives

VISION: Safe, flexible, reliable, and resilient plug-n-play building block, that can be used individually or scaled as needed, to address a range of applications and fulfill the electric power needs of off-grid and poor-grid homes and communities.

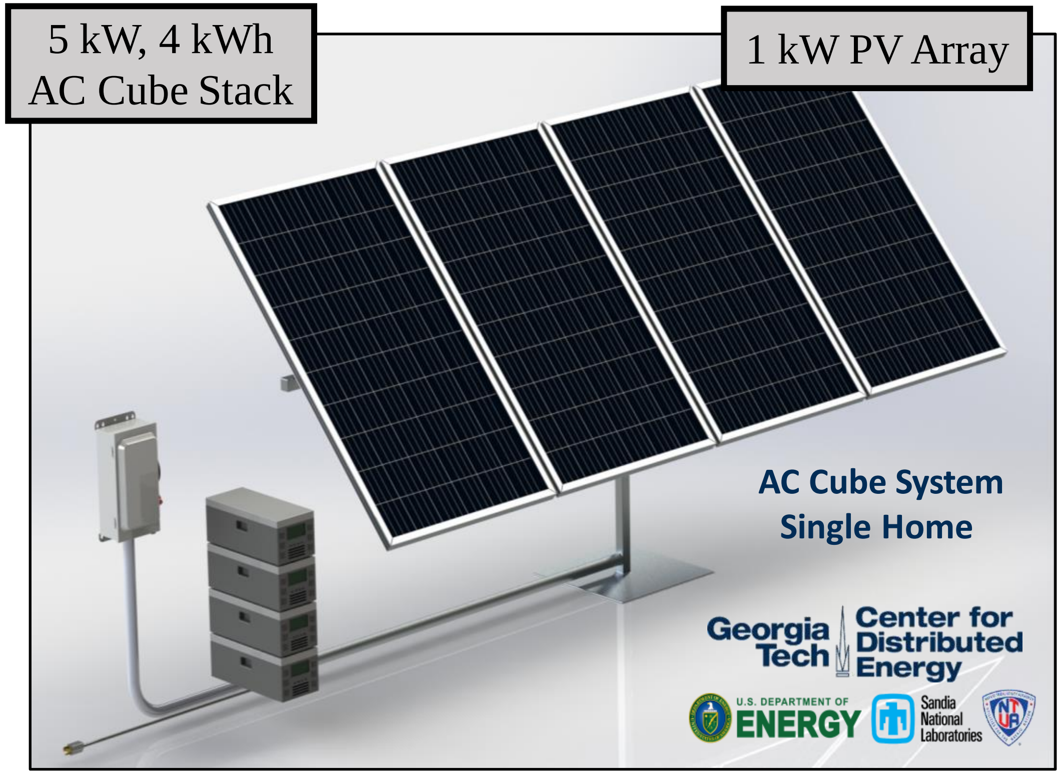
Storyboarding the Requirements:

Worked with the Derrick Terry of the Navajo Tribal Utility Authority (NTUA) and Sandia to better understand the needs, pain- points and use-cases that are typical for an energy constrained community such as the Navajo Nation

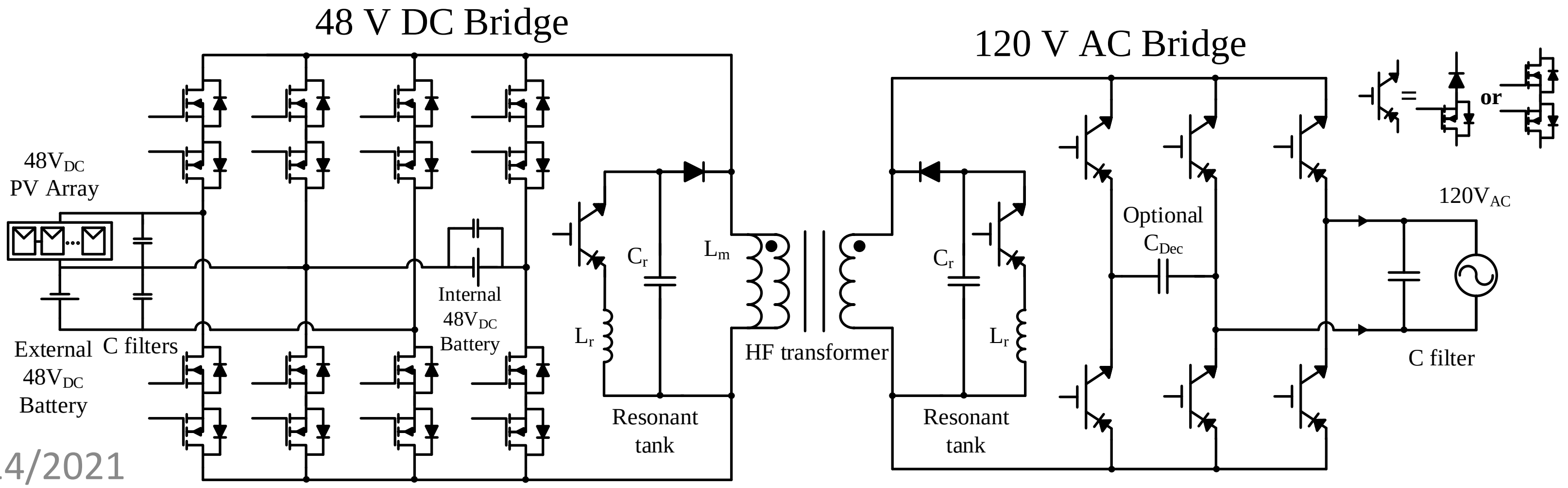
- Plug and play allows rapid installation and minimum down-time in resiliency situations
- Touch safe (48 VDC) batteries and PV panels allow homeowners to self-install the system
- Multi-port operation: 120 V AC, solar, batteries, grid, and loads – managing all simultaneously
- Flexible – can support individual loads, or can be stacked to support a house
- Can automatically form a microgrid with other homes if needed
- Automatically supports grid-connected, microgrid, and portable power applications
- Can export power to the grid (if allowed by utility)
- Monitoring and control of the system via cell phones
- Baked in safety and cybersecurity
- No skilled technicians needed to install, operate and maintain – ‘PhD in the Box’

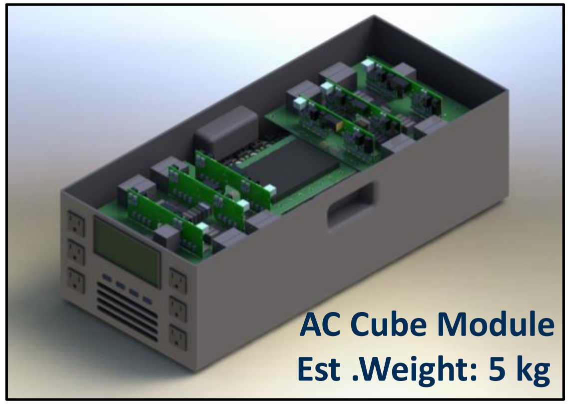
Building Block - AC Cube

- “AC Cube” w/ 1 kWh internal storage, 120 VAC 1 kW
- Soft-switching S4T topology for high efficiency, low EMI, low THD
- Integrated and external 48 V DC battery and 24-48 V PV panels
- Easy install & flexible support of multiple loads w/o house rewiring
- Parallel modules for higher output power or longer run time
- Return power from PV panels to AC grid under normal conditions
- Advanced diagnostics and system control via smart phone

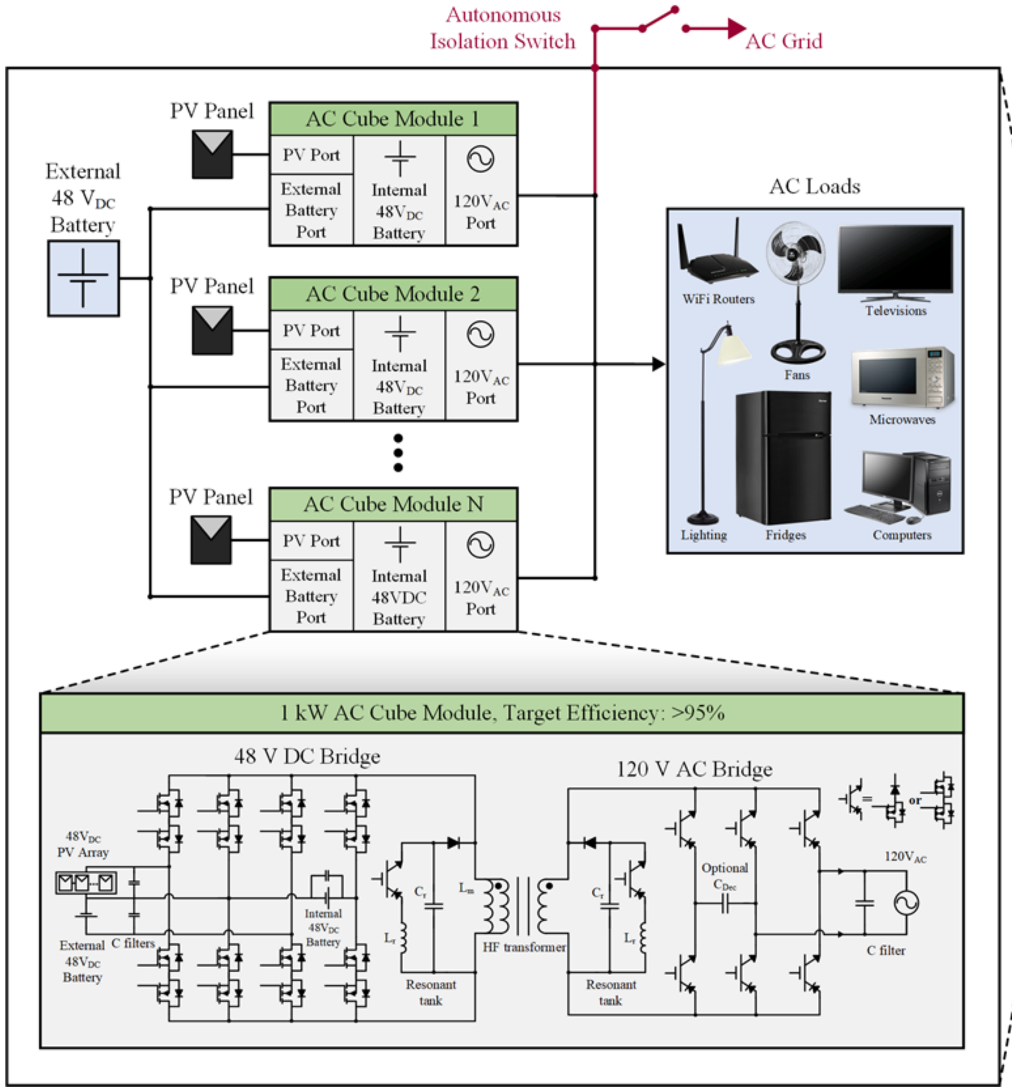


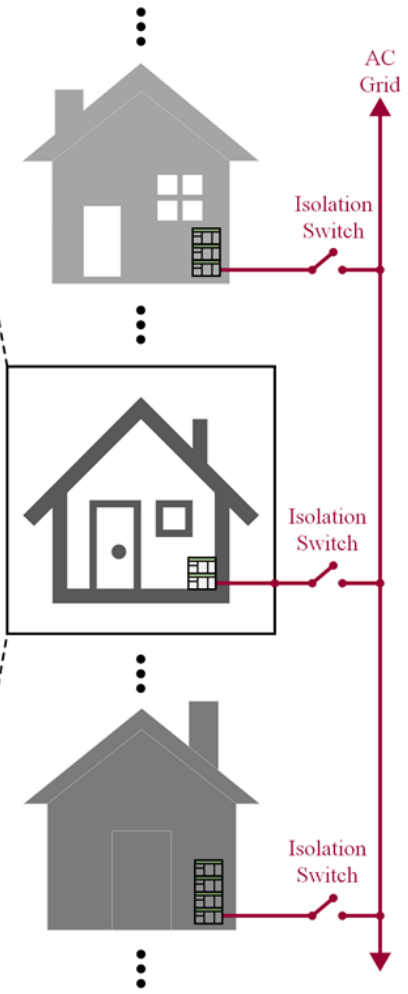
Target 95% Efficient S4T Multiport Converter





AC Cube System Overview





- 1.25 kW “AC Cube” 250 W PV panel and 1 kWh internal and external 48 VDC battery
- Stack AC Cubes for higher power, add extra batteries & PV panels for longer run times.
- Connect to grid at main AC panel to supply sub-circuits or to return power (needs electrician).
- Individual AC Cube modules can be moved to whichever load needs power.
- Plug-n-play connect of multiple stacks of AC Cubes to form an adhoc microgrid
- Target <$1000 for 1.25 kW/1 kWHr AC Cube w/ internal battery, 250 W PV panel, grid connect
- Realize up to $350/year of energy savings per AC Cube (assuming $0.30/kWh in CA).
- Diagnostics and system control via smart phone.

How do you get this level of autonomous flexible control?

Collaborative Control for Grid as an Ecosystem

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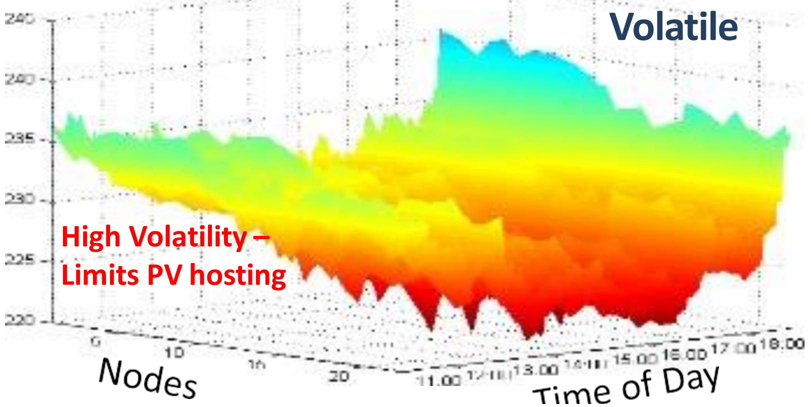
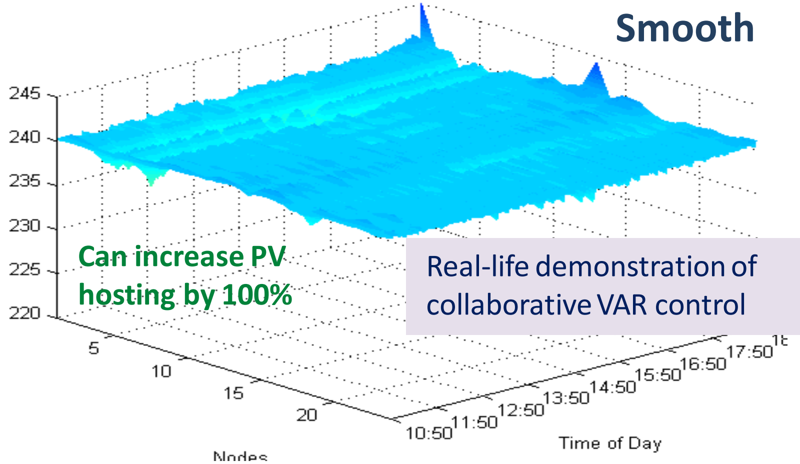
- Centralized control of a future grid with millions of intelligent DERs (storage) will be challenging – complexity, comms latency, security
- 'Collaborative Control' allows edge devices (inverters) to use local measurements and standard 'rules', acting in real-time to fulfill individual goals, and collaborating to sustain the grid ecosystem
- System is constantly changing, and devices need to act without real-time knowledge of system topology/state or low-latency comms
- Fundamentally different paradigm: today devices view the grid as a resource – with an ecosystem, all need to act to sustain it (priority)

Source: Southern Company and Varentec



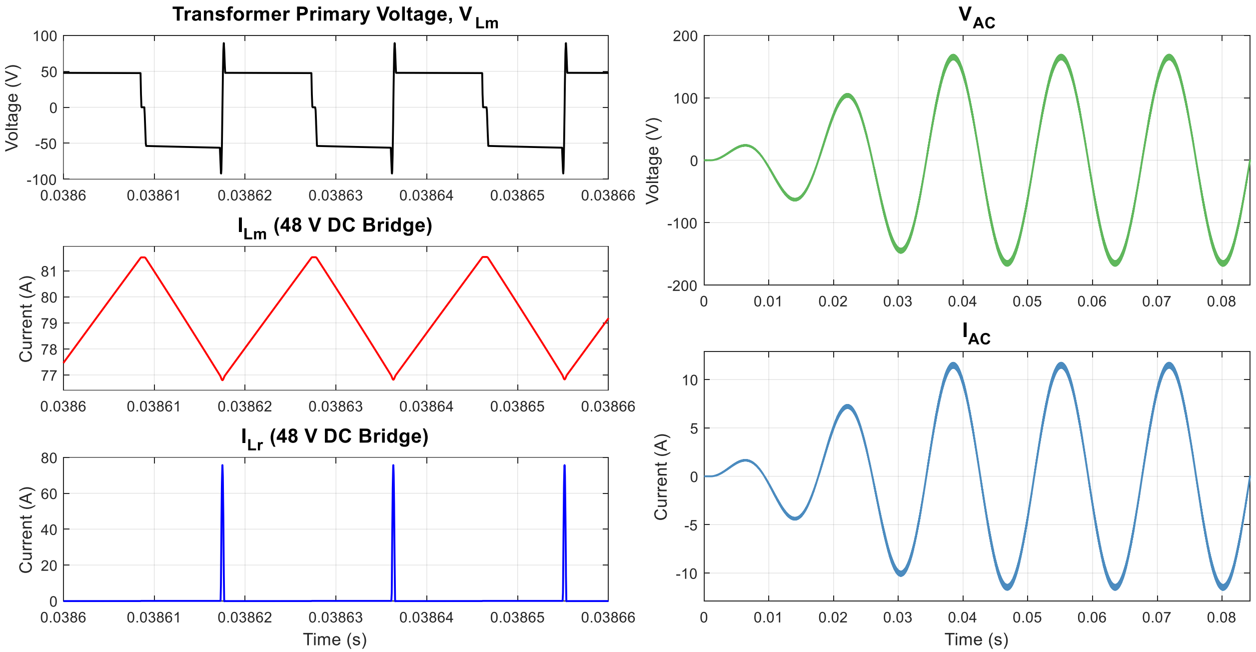


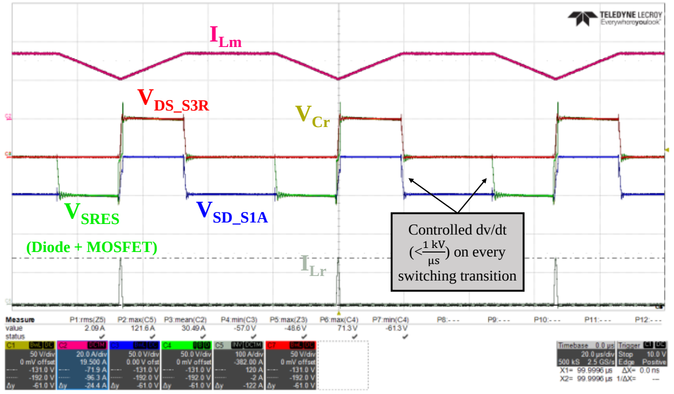
Examples of collaboration without communications

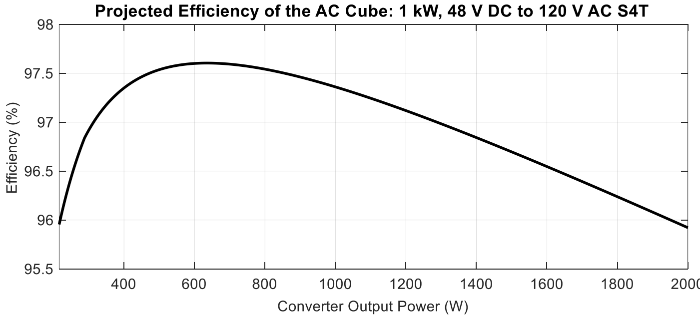
Autonomous inverters that collaborate with minimal system knowledge, don't interact, operate over wide range of conditions & coordinate with slow secure comms

AC Cube Validation

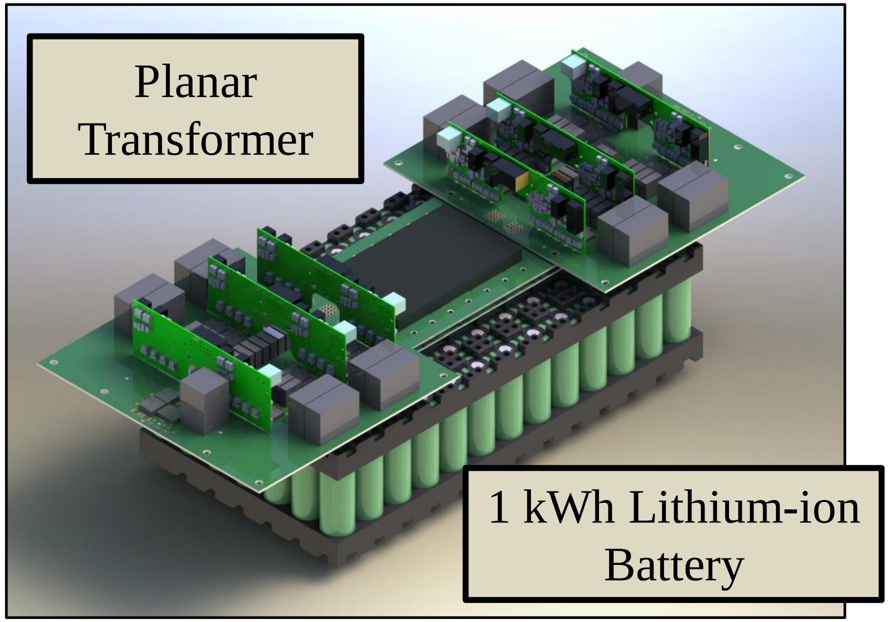
- Validation of AC Cube at 120 V AC (RMS), 1.25 kW (2 kW peak).
- Projected AC Cube efficiency >96% over wide operating range
- Control capability in multiport and microgrid operation validated

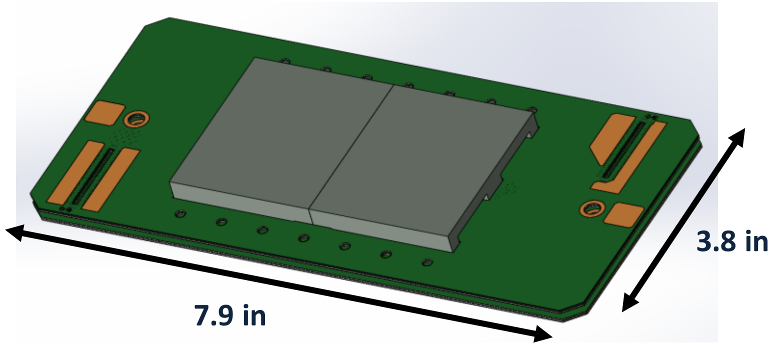






AC Cube single module simulation & experimental results

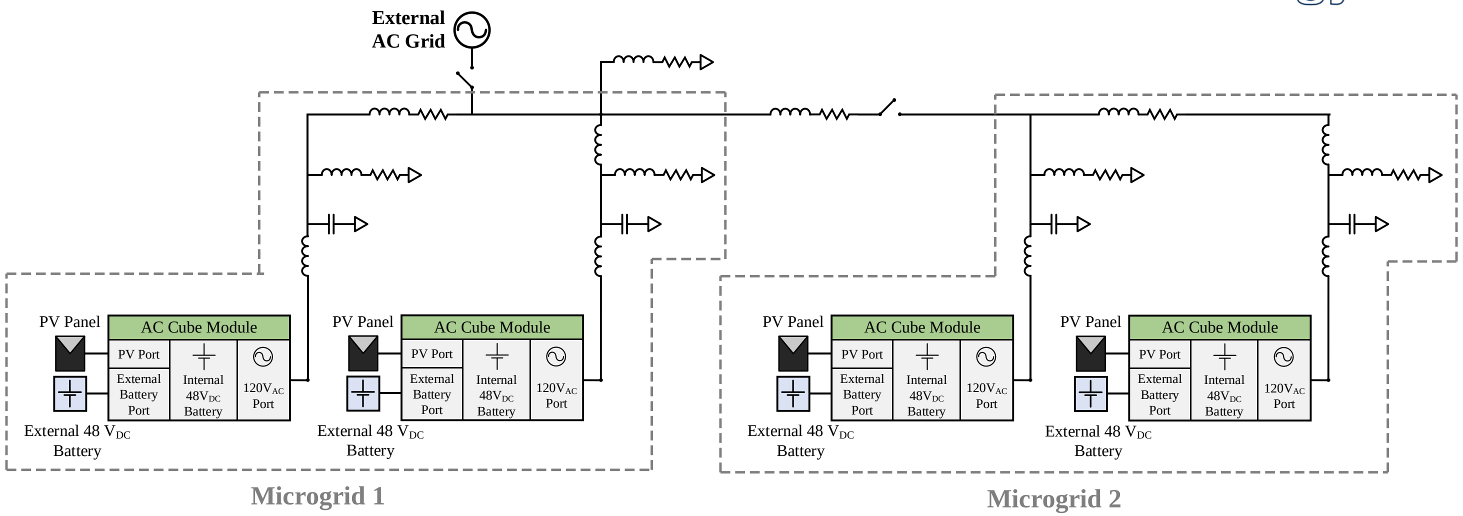


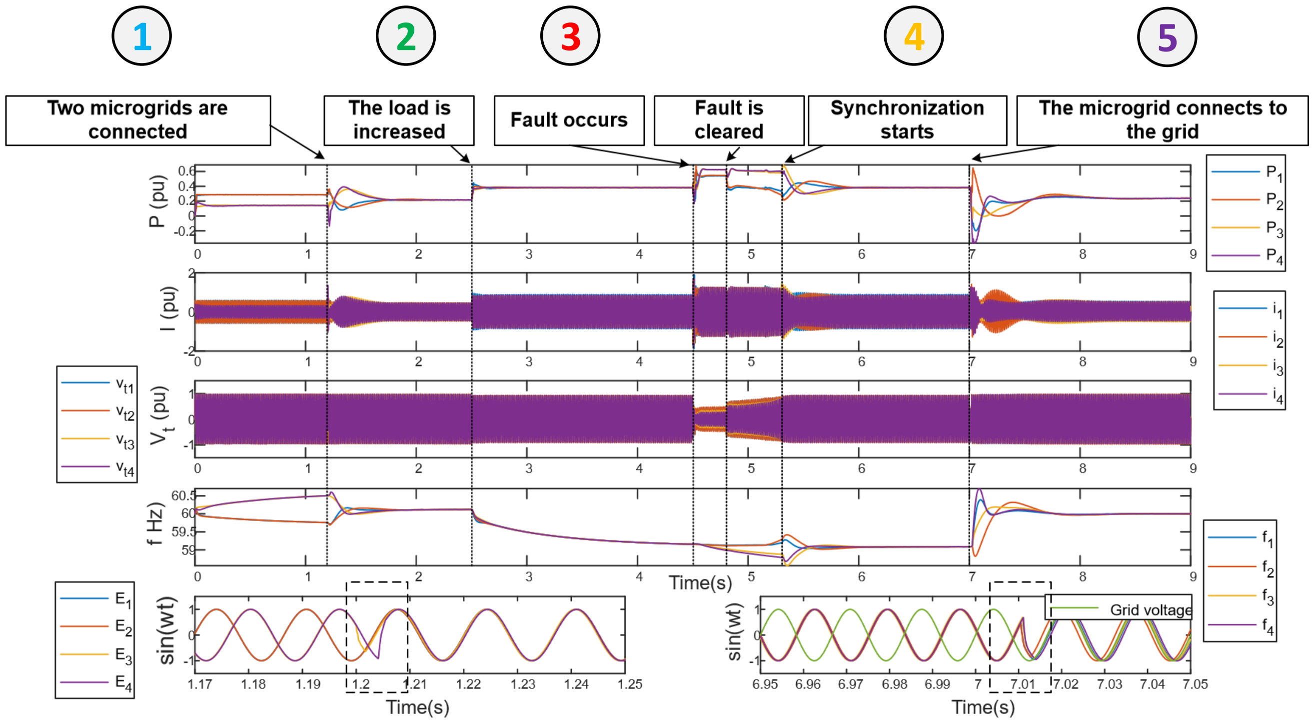


Planar transformer w/ integrated current sensing

Collaborative Microgrid Control

- The AC Cube features a variety of standalone, grid-following, grid-firming, and grid-forming operational modes
- Proposed universal control strategy incorporates P-F droop and <u>ability to connect/disconnect at will with grid or other AC Cubes</u>
- Preliminary simulations on a 4-module system (2 microgrids each with 2 modules) evidence stability of the proposed control strategy during:
    1. Connection of multiple islanded microgrids
    2. Load step changes
    3. Grid fault conditions
    4. Re-synchronization following grid fault clearance
    5. Connection of microgrid clusters to external grid





AC Cube - Use Scenarios

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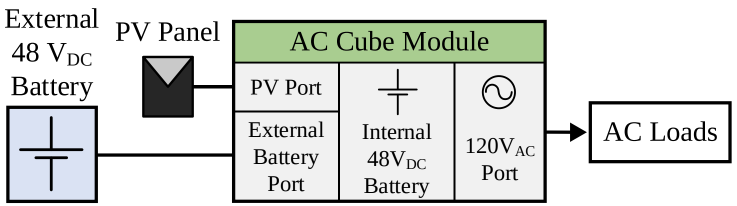
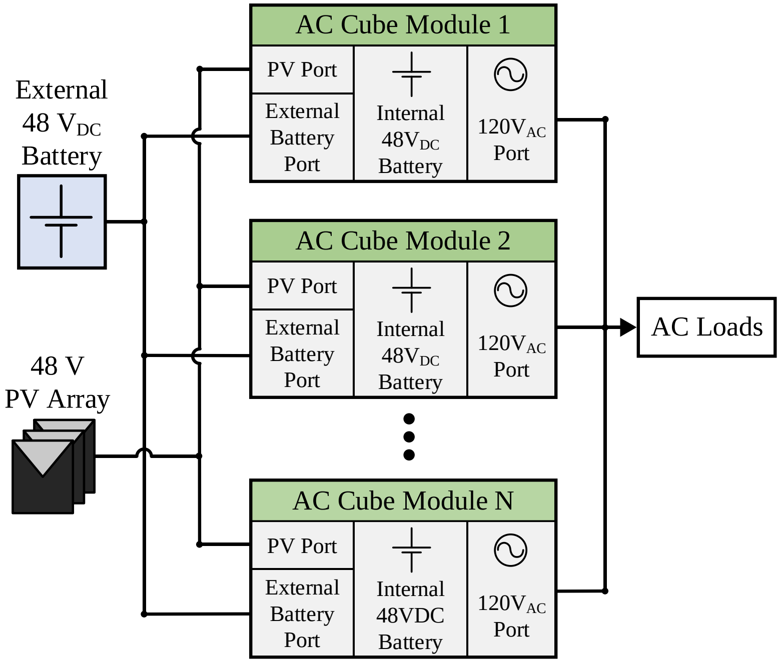
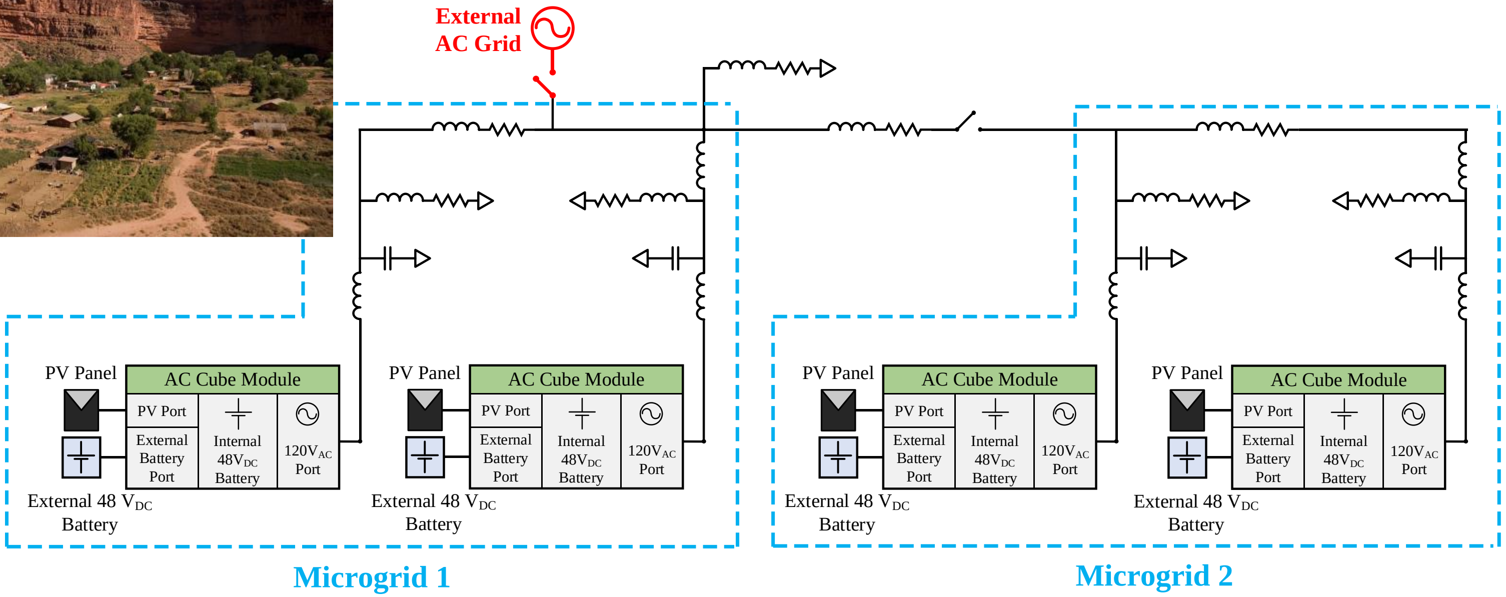


1a. Standalone Single AC Cube Module

3. For emergency deployments in resiliency conditions, ship or airdrop, and rapidly deploy using plug-n-play modules.



1b. Standalone Stacked AC Cube Modules



2. Two Microgrid Systems with Two AC Cubes Each

AC Cube Attributes and Project Timeline

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- AC Cube delivers low-cost AC power while being uniquely suited to the following requirements of the Navajo Nation and for resilient communities:
  - Intrinsic safety for rapid installation by electrically untrained members
  - Portable plug-and-play AC power for work and community ceremonies
  - Stacking of modules enables output power scalability and incremental investments
  - Low hardware and installation cost, rapid install, flexible configurability
  - Collaborative control enables variety of grid-forming, grid-following & microgrid operating modes
  - Integrated power monitoring enables “distributed utility” service-based models through NTUA

No.	Task	Duration
Yr 1	Work with NTUA to develop detailed specification. Develop concept for solution.	Aug 2020 - Sep 2020
Yr 2	Prove new elements to validate function. Detailed design of AC Cube. Simulate AC Cube for functionality. Detailed mechanical design of device and system. Procure and assemble first prototype AC Cube.	Oct 2020- Sept 2021
Yr 3	Build and demonstrate fully functional prototype at CDE. Build two AC Cubes after validation. Opal-RT demonstration of AC Cube based microgrid system. Demonstrate a multi AC Cube system in lab, including internal/external storage and adhoc microgrid functionality. Ship prototype to Sandia. Write final report.	Oct 2021– Sep 2022

IEEE Empower a Billion Lives - II

Energy Access needs new fresh thinking – holistic solutions, high-impact, scalable and lower cost

Key Challenge:

- 3 billion live in extreme energy poverty, ~1 billion live off-grid (only 15 million have Tier 2 (>200Wh/day)
- Solving energy access with today's solutions will result in 3.7 Gtons of CO_2 emission – not OK
- Existing assumptions relying on grid extension, SHS & microgrids are not working out as expected

Challenges:

- **Don't need energy – need livelihood and services**
- Factors - low purchasing power, aspirations, neighbors
- Low-tech users, interoperability, tech-obsolescence
- Last-mile sale, commission and maintain challenges
- Scalable - start small & grow as needed
- Need flexible and sustainable business models.

IEEE Empower a Billion Lives (EBL) is an interdisciplinary global competition to develop/demonstrate innovative solutions to energy poverty & resiliency.

Teams are invited from across the globe and from all walks of life, including companies, research organizations, entrepreneurial startups, as well as student teams from colleges and universities.

Participating in EBL-II is easy. Log on to www.empowerabillionlives.org to register your team. Review the requirements and submit a brief 3-page Concept Paper in the required format by Nov 1, 2021.

Building on the success of Empower a Billion Lives – I (EBL-I), IEEE PELS has launched EBL-II. EBL-I was held in 2019 and attracted over 450 teams from 70 countries. Over $500,000 was awarded to teams in prizes and support. Grand prize of $100,000 was won by Team SoULS from IIT Bombay, India

Conclusions

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- **VISION:** A future grid that realizes reliability and resiliency from the grid edge, and access to low-cost energy from the bulk power system, when it is available
- One key element to achieve this goal is a flexible plug-n-play power-brick which addresses the needs of off-grid communities, such as the Navajo Nation, as well as community resiliency after an HILF event
- The 1.25 kW, 1 kWh AC Cube module provides such a building block and supports most residential loads, and multiple modules can be connected in parallel to increase output power and run time.
- The AC Cube eliminates the need for skilled technician install and operation through a plug-n-play design, use of advanced collaborative controls, and intrinsic electrical safety.
- The proposed universal control scheme enables both stand-alone and grid-connected applications, enabling a variety of system installation possibilities in resiliency and contingency scenarios.

Project members would like to thank Dr Imre Gyuk from DOE for his guidance and support, and Stan Atcitty from Sandia Labs for his guidance and technical leadership

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Questions?

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